

VILLANI CONJECTURE ON SMOOTHING EFFECT OF THE HOMOGENEOUS BOLTZMANN EQUATION WITH MEASURE INITIAL DATUM

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ABSTRACT. The purpose of this paper is to prove Villani conjecture on the smoothing effect of the homogeneous Boltzmann equation without angular cutoff, that is, to show that any weak solution to the Cauchy problem with measure initial datum except a single Dirac mass acquires C^∞ regularity in the velocity variable in any positive time. We consider the Maxwellian molecule type cross section. The key point is to obtain a time degenerate coercivity estimate.

1. INTRODUCTION

We consider the spatially homogeneous Boltzmann equation

$$(1.1) \quad \partial_t f(t, v) = Q(f, f)(t, v),$$

where $f(t, v)$ is the density distribution of particles with velocity $v \in \mathbb{R}^3$ at time t . The right hand side of (1.1) is given by the Boltzmann bilinear collision operator

$$Q(g, f)(v) = \int_{\mathbb{R}^3} \int_{\mathbb{S}^2} B(v - v_*, \sigma) \{g(v'_*)f(v') - g(v_*)f(v)\} d\sigma dv_*,$$

where for $\sigma \in \mathbb{S}^2$

$$v' = \frac{v + v_*}{2} + \frac{|v - v_*|}{2} \sigma, \quad v'_* = \frac{v + v_*}{2} - \frac{|v - v_*|}{2} \sigma,$$

which follow from the conservation of momentum and energy,

$$v' + v'_* = v + v_*, \quad |v'|^2 + |v'_*|^2 = |v|^2 + |v_*|^2.$$

The equation (1.1) is supplemented with a non-negative initial datum

$$(1.2) \quad f(0, v) = f_0(v),$$

which is the density of probability distribution (more generally a probability measure).

The non-negative cross section $B(z, \sigma)$ depends only on $|z|$ and the scalar product $\frac{z}{|z|} \cdot \sigma$. For physical models, it usually takes the form

$$B(|v - v_*|, \cos \theta) = \Phi(|v - v_*|)b(\cos \theta), \quad \cos \theta = \frac{v - v_*}{|v - v_*|} \cdot \sigma, \quad 0 \leq \theta \leq \frac{\pi}{2},$$

2010 *Mathematics Subject Classification.* primary 35Q20, 76P05, secondary 35H20, 82B40, 82C40,

Key words and phrases. Boltzmann equation, smoothing effect, measure initial datum, coercivity estimate.

where

$$(1.3) \quad \Phi(|z|) = \Phi_\gamma(|z|) = |z|^\gamma, \text{ for some } \gamma > -3,$$

$$(1.4) \quad b(\cos \theta) \theta^{2+2s} \rightarrow K \text{ when } \theta \rightarrow 0+, \text{ for } 0 < s < 1 \text{ and } K > 0.$$

In fact, if the inter-particle potential satisfies the inverse power law $U(\rho) = \rho^{-(q-1)}$, $q > 2$, where ρ denotes the distance between two interacting particles, then s and γ are given by

$$s = 1/(q-1) < 1, \quad \gamma = 1 - 4s = 1 - 4/(q-1) > -3.$$

For this physical model, we have $\gamma = 0$ if $s = 1/4$, which is called the Maxwellian molecule. Inspired by this case, we consider the Maxwellian molecule type cross section when

$$\gamma = 0, \quad 0 < s < 1.$$

The angle θ is the deviation angle, i.e., the angle between pre- and post- collisional velocities. The range of θ is in an interval $[0, \pi]$, but as in [20] it is customary to restrict it to $[0, \pi/2]$, by replacing $b(\cos \theta)$ by its “symmetrized” version

$$[b(\cos \theta) + b(\cos(\pi - \theta))] \mathbf{1}_{0 \leq \theta \leq \pi/2},$$

which is possible due to the invariance of the product $f(v')f(v'_*)$ in the collision operator $Q(f, f)$ under the change of variables $\sigma \rightarrow -\sigma$. It should be noted that $b(\cos \theta)$ has the integrable singularity, that is,

$$\int_{\mathbb{S}^2} b\left(\frac{v - v_*}{|v - v_*|} \cdot \sigma\right) d\sigma = 2\pi \int_0^{\pi/2} b(\cos \theta) \sin \theta d\theta = \infty.$$

The case where $0 < s < 1/2$, that is, $\int_0^{\pi/2} \theta b(\cos \theta) \sin \theta d\theta < \infty$ is called the mild singularity, and another case $1/2 \leq s < 1$ is called the strong singularity. This kind of singularity leads to the gain of regularity in the solution.

The study on the homogeneous Boltzmann equation has a very long history, cf. [7, 5] and the references in recent work [12]. In particular, the smoothing effect of (weak) solutions to the Cauchy problem for the non cutoff homogeneous Boltzmann equation has been studied by many authors in [9, 2, 3, 14, 10, 4, 8], including Gevrey smoothing effect in [15]. However, the problem for measure initial data has been studied only in [13], when it consists of a sum of four Dirac masses.

On the other hand, Villani conjecture[21] is to show that the smoothing effect for weak measurable solutions holds for any measure initial data except a single Dirac mass. The purpose of this paper is to justify this conjecture, which is optimal in the sense that a single Dirac mass is a stationary solution of the Boltzmann equation.

Let us now introduce some notations for function spaces and recall some related works on the existence and uniqueness. For every $0 \leq \alpha < \infty$, we denote by $P_\alpha(\mathbb{R}^d)$ the class of all probability measure F on \mathbb{R}^d , $d \geq 1$, such that

$$\int_{\mathbb{R}^d} |v|^\alpha dF(v) < \infty.$$

Concerning the Cauchy problem for the homogeneous Boltzmann equation of the Maxwellian molecule type cross section, Tanaka [17] in 1978 proved the existence and the uniqueness of the solution in the space $P_2(\mathbb{R}^d)$ by using probability theory. The proof of this result was simplified and generalized in [16, 18].

The existence of solution with bounded energy was extended in [6] to the initial datum as a probability measure with infinite energy. Precisely, following [6], introduce

Definition 1.1. A function $\psi : \mathbb{R}^3 \rightarrow \mathbb{C}$ is called a characteristic function if there is a probability measure Ψ (i.e., a positive Borel measure with $\int_{\mathbb{R}^3} d\Psi(v) = 1$) such that the identity $\psi(\xi) = \int_{\mathbb{R}^3} e^{-iv \cdot \xi} d\Psi(v)$ holds. We denote the set of all characteristic functions by \mathcal{K} .

Inspired by [18], a subspace \mathcal{K}^α for $\alpha \geq 0$ was defined in [6] as follows:

$$(1.5) \quad \mathcal{K}^\alpha = \{\varphi \in \mathcal{K} ; \|\varphi - 1\|_\alpha < \infty\},$$

where

$$(1.6) \quad \|\varphi - 1\|_\alpha = \sup_{\xi \in \mathbb{R}^3} \frac{|\varphi(\xi) - 1|}{|\xi|^\alpha}.$$

The space \mathcal{K}^α endowed with the distance

$$(1.7) \quad \|\varphi - \tilde{\varphi}\|_\alpha = \sup_{\xi \in \mathbb{R}^3} \frac{|\varphi(\xi) - \tilde{\varphi}(\xi)|}{|\xi|^\alpha}$$

is a complete metric space (see Proposition 3.10 of [6]). It follows that $\mathcal{K}^\alpha = \{1\}$ for all $\alpha > 2$ and the embeddings (Lemma 3.12 of [6]) hold, that is,

$$\{1\} \subset \mathcal{K}^\alpha \subset \mathcal{K}^\beta \subset \mathcal{K}^0 = \mathcal{K} \quad \text{for all } 2 \geq \alpha \geq \beta \geq 0.$$

The definition of the space \mathcal{K}^α is natural because we have the following lemma (Lemma 3.15 of [6]).

Lemma 1.2. Let Ψ be a probability measure on \mathbb{R}^3 such that

$$(1.8) \quad \begin{aligned} &\exists \alpha \in (0, 2]; \int |v|^\alpha d\Psi(v) < \infty, \\ &\text{and moreover, } \int v_j d\Psi(v) = 0, j = 1, 2, 3, \text{ when } \alpha > 1. \end{aligned}$$

Then the Fourier transform of Ψ , that is, $\psi(\xi) = \int e^{-iv \cdot \xi} d\Psi(v)$ belongs to \mathcal{K}^α .

The inverse of the lemma does not hold, in fact, the space \mathcal{K}^α is bigger than the set of the Fourier transform of P_α (Remark 3.16 of [6]). So we introduce $\tilde{P}_\alpha = \mathcal{F}^{-1}(\mathcal{K}^\alpha)$ endowed also with the distance (1.7). The existence and the uniqueness of the solution in the space \tilde{P}_α was proved in [6] for the mild singularity, and has been recently improved in [13] for the strong singularity. Namely, if the cross section $b(\cos \theta)$ satisfies (1.3) with $0 < s < 1$ and if $2s < \alpha \leq 2$, then there exists a unique solution to the Cauchy problem (1.1)-(1.2) in the space $C([0, \infty), \tilde{P}_\alpha)$ for any initial datum in \tilde{P}_α (see Theorem 3.1 in the Appendix).

We are now ready to state the main results of this paper.

Theorem 1.3. Let $b(\cos \theta)$ satisfy (1.3) with $0 < s < 1$ and let $\alpha \in (2s, 2]$. If $F_0 \in \tilde{P}_\alpha(\mathbb{R}^3)$ is not a single Dirac mass and $f(t, v)$ is a unique solution in $C([0, \infty), \tilde{P}_\alpha)$ to the Cauchy problem (1.1)-(1.2), then there exists a $T > 0$ such that $f(t, \cdot) \in H^\infty(\mathbb{R}^3)$ for any $0 < t \leq T$. Moreover, if $F_0 \in P_2(\mathbb{R}^3)$ then $T = \infty$.

Lemma 1.4. *Let $F_0 \in \tilde{P}_\alpha(\mathbb{R}^3)$ and $f(t, v) \in C([0, \infty), \tilde{P}_\alpha)$ be the same as in Theorem 1.3. If $\psi(t, \xi)$ and $\psi_0(\xi)$ are Fourier transforms of $f(t, v)$ and F_0 , respectively, then there exist $T > 0$ and $C > 0$, such that for $t \in [0, T]$ we have*

$$(1.9) \quad t \int_{\mathbb{R}^3} \langle \xi \rangle^{2s} |h(\xi)|^2 d\xi \leq C \left(\int_{\mathbb{R}^3} \left(\int_{\mathbb{S}^2} b\left(\frac{\xi}{|\xi|} \cdot \sigma\right) (1 - |\psi(t, \xi^-)|) d\sigma \right) |h(\xi)|^2 d\xi \right. \\ \left. + \int_{\mathbb{R}^3} |h(\xi)|^2 d\xi \right), \quad \text{for } \forall h \in L_s^2,$$

where $\xi^- = (\xi - |\xi|\sigma)/2$.

With Lemma 1.4, the proof of Theorem 1.3 can be given as follows.

Proof of Theorem 1.3. It follows from the Bobylev formula that the Cauchy problem (1.1)-(1.2) is reduced to

$$(1.10) \quad \begin{cases} \partial_t \psi(t, \xi) = \int_{\mathbb{S}^2} b\left(\frac{\xi \cdot \sigma}{|\xi|}\right) \left(\psi(t, \xi^+) \psi(t, \xi^-) - \psi(t, \xi) \psi(t, 0) \right) d\sigma, \\ \psi(0, \xi) = \psi_0(\xi), \quad \text{where } \xi^\pm = \frac{\xi}{2} \pm \frac{|\xi|}{2} \sigma. \end{cases}$$

By Theorem 3.1, $\psi(t, \xi) \in C([0, \infty), \mathcal{K}^\alpha)$. Define a time dependent weight function

$$M_\delta(t, \xi) = \langle \xi \rangle^{Nt^2-4} \langle \delta \xi \rangle^{-2N_0}, \quad \langle \xi \rangle^2 = 1 + |\xi|^2,$$

where $N_0 = NT^2/2 + 2$, $N \in \mathbb{N}$ and $\delta > 0$. We multiply the first equation of (1.10) by $M_\delta(t, \xi)^2 \overline{\psi(t, \xi)}$ and integrate with respect to ξ over \mathbb{R}^3 . Denote $\psi^\pm = \psi(t, \xi^\pm)$ and $M^\pm = M_\delta(t, \xi^\pm)$ to simplify the notation and note that

$$\begin{aligned} -2\text{Re} \left\{ (\psi^+ \psi^- - \psi) M^2 \overline{\psi} \right\} &= \left(|M\psi|^2 + |M^+ \psi^+|^2 - 2\text{Re} \left\{ \psi^- (M^+ \psi^+) \overline{M\psi} \right\} \right) \\ &\quad + \left(|M\psi|^2 - |M^+ \psi^+|^2 \right) + 2\text{Re} \left\{ \psi^- ((M - M^+) \psi^+) \overline{M\psi} \right\} \\ &= J_1 + J_2 + J_3. \end{aligned}$$

Using the Cauchy-Schwarz inequality for the third term of J_1 , we have

$$J_1 \geq (1 - |\psi^-|) \left(|M\psi|^2 + |M^+ \psi^+|^2 \right) \geq (1 - |\psi^-|) |M\psi|^2.$$

Therefore, by means of (1.9) we get

$$(1.11) \quad \int_{\mathbb{R}^3 \times \mathbb{S}^2} b\left(\frac{\xi}{|\xi|} \cdot \sigma\right) J_1 d\sigma d\xi + \int_{\mathbb{R}^3} |M\psi|^2 d\xi \gtrsim t \int_{\mathbb{R}^3} \langle \xi \rangle^{2s} |M\psi|^2 d\xi,$$

where $A \gtrsim B$ means that there exists a constant $C_0 > 0$ such that $A \geq C_0 B$. If we use the change of variable $\xi \rightarrow \xi^+$ for the term $M^+ \psi^+$ in J_2 , by the cancellation lemma (Lemma 1 of [1]), we have

$$\begin{aligned} &\left| \int_{\mathbb{R}^3 \times \mathbb{S}^2} b\left(\frac{\xi}{|\xi|} \cdot \sigma\right) J_2 d\sigma d\xi \right| \\ &= 2\pi \left| \int_{\mathbb{R}^3} |M\psi|^2 \left(\int_0^{\pi/2} b(\cos \theta) \sin \theta \left(1 - \frac{1}{\cos^3(\theta/2)} \right) d\theta \right) d\xi \right| \\ &\lesssim \int_{\mathbb{R}^3} |M\psi|^2 d\xi, \end{aligned}$$

where $A \lesssim B$ means that there exists a constant $C_0 > 0$ such that $A \leq C_0 B$. Since $|M - M^+| \lesssim \sin^2(\theta/2)M^+$ (see (3.4) of [14]), by the Cauchy-Schwarz inequality we also have the same upper bound estimate for J_3 by using again the change of variable $\xi \rightarrow \xi^+$ for the term including $M^+\psi^+$. Since

$$2\operatorname{Re}\left(\frac{\partial\psi}{\partial t}M^2\overline{\psi}\right) = \frac{\partial|M\psi|^2}{\partial t} - 4Nt\log\langle\xi\rangle|M\psi|^2,$$

and $|\xi|^{2s}/\log\langle\xi\rangle \rightarrow \infty$ as $|\xi| \rightarrow \infty$, we have

$$\frac{d}{dt} \int_{\mathbb{R}^3} |M_\delta(t, \xi)\psi(t, \xi)|^2 d\xi \lesssim \int_{\mathbb{R}^3} |M_\delta(t, \xi)\psi(t, \xi)|^2 d\xi,$$

which gives for $t \in (0, T]$

$$\int_{\mathbb{R}^3} |\langle\xi\rangle^{Nt^2-4} (1 + \delta|\xi|^2)^{-N_0} \psi(t, \xi)|^2 d\xi \lesssim \int_{\mathbb{R}^3} |\langle\xi\rangle^{-4} \psi_0(\xi)|^2 d\xi.$$

Letting $\delta \rightarrow 0$, we obtain the first part of Theorem 1.3 because we can take an arbitrarily large N .

We now turn to the second part of the theorem when $F_0 \in P_2(\mathbb{R}^3)$. Since the conservation of energy holds, we have $\int |v|^2 f(T, v) dv = \int |v|^2 dF_0(v)$. In view of $f(T, v) \in L^\infty(\mathbb{R}^3)$ we obtain

$$\|f(T)\|_{L \log L} := \int f(T, v) \log(1 + f(T, v)) dv < \infty,$$

so that $f(T) \in L_2^1 \cap L \log L$. It follows from Theorem 1 in [19] that

$$(1.12) \quad \sup_{t \geq T} \left(\|f(t)\|_{L_2^1} + \|f(t)\|_{L \log L} \right) < \infty,$$

which shows that there exists a $\kappa > 0$ independent of $t \geq T$ such that

$$1 - |\psi(t, \xi)| \geq \kappa \min(1, |\xi|^2),$$

by means of Lemma 3 in [1]. Therefore, for $|\xi| \geq R$ for some $R > 0$ suitably large, we have

$$\begin{aligned} \int_{\mathbb{S}^2} b\left(\frac{\xi}{|\xi|} \cdot \sigma\right) (1 - |\psi(t, \xi^-)|) d\sigma &\geq 2\pi\kappa \int_0^{|\xi|^{-1}} b(\cos\theta) |\xi^-|^2 \sin\theta d\theta \\ &\gtrsim |\xi|^2 \int_0^{|\xi|^{-1}} \theta^{1-2s} d\theta \gtrsim |\xi|^{2s}, \end{aligned}$$

which gives the standard coercivity estimate instead of (1.9). Hence this leads us to $f(t, v) \in H^\infty(\mathbb{R}^3)$ for $\forall t > T$ by the same argument used in [14]. \square

The rest of the paper will be organized as follows. In the next section, we will prove Lemma 1.4 about the degenerate coercivity estimate which is the key estimate to show the smoothing effect. And in the Appendix, we will recall the existence and uniqueness result obtained in [6, 13] and show the continuity of the time derivative of the solution which is needed in Section 2.

2. DEGENERATE COERCIVITY ESTIMATE

To obtain the coercivity estimate for measure value function which is not concentrated at a single point, we will consider two cases, that is, the case when the measure is concentrated on a straight line and otherwise. Unlike the standard coercivity estimate obtained in the previous works, the key observation is that the coercivity estimate is degenerate in the time variable as shown in Lemma 1.4. That is, one can not expect to have a gain of regularity of order $2s$ uniformly up to initial time. For this, we need to consider the time derivative of $\psi(t, \xi^-)$ in the case when ξ is parallel to the straight line of the concentration of the measure. For clear presentation, the coercivity is estimated in the following two subsections.

2.1. Initial measure not concentrated on a straight line. We now consider the case when $F_0(v)$ is not concentrated on a straight line. In this case, without loss of generality, we can assume that there exist three small balls denoted by $A_i = B(\mathbf{b}_i, \delta)$ with center at $v = \mathbf{b}_i$ and radius $\delta > 0$ such that $\int_{A_i} dF_0(v) = m_i > 0$, for $i = 1, 2, 3$. Up to a linear coordinate transform, we can assume $\mathbf{b}_1 = \mathbf{0}$, \mathbf{b}_2 and \mathbf{b}_3 are linearly independent. That is

$$\eta_0 = 1 - \left| \frac{\mathbf{b}_2}{|\mathbf{b}_2|} \cdot \frac{\mathbf{b}_3}{|\mathbf{b}_3|} \right| = 1 - |\cos \alpha| > 0,$$

where α is the angle between \mathbf{b}_2 and \mathbf{b}_3 . Take two positive constants $d_1 < d_2$ such that

$$0 < d_1 \min\{|\mathbf{b}_2|, |\mathbf{b}_3|\} < d_2 \max\{|\mathbf{b}_2|, |\mathbf{b}_3|\} \leq \frac{\pi}{2}.$$

Put $d = (d_1 + d_2)/2$. Firstly, we assume that ξ^- varies on the circle

$$(2.1) \quad \mathcal{C} = \{\xi \in \mathbb{R}^3; |\xi| = d, \xi \perp (\mathbf{b}_2 \times \mathbf{b}_3)\}.$$

In the following discussion, we choose $\delta > 0$ to be sufficiently small.

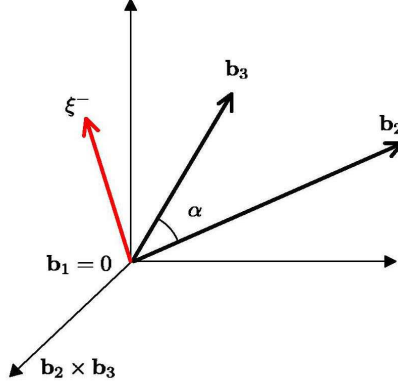


FIGURE 1. ξ^- and three vectors $\mathbf{b}_1, \mathbf{b}_2, \mathbf{b}_3$

Denote

$$\int_{A_j} e^{iv \cdot \xi^-} dF(v) = m_j(a_j + ib_j), \quad j = 1, 2, 3.$$

Note that $|a_j + ib_j| \leq 1$. With the above notations, it is straightforward to check that

$$\begin{aligned}(a_1, b_1) &= (1, 0) + \mathbf{e}_1, \\ (a_2, b_2) &= (\cos(|\xi^-| \|\mathbf{b}_2\| \cos \gamma_1), \sin(|\xi^-| \|\mathbf{b}_2\| \cos \gamma_1)) + \mathbf{e}_2, \\ (a_3, b_3) &= (\cos(|\xi^-| \|\mathbf{b}_3\| \cos \gamma_2), \sin(|\xi^-| \|\mathbf{b}_3\| \cos \gamma_2)) + \mathbf{e}_3,\end{aligned}$$

where γ_1 is the angle between the vectors ξ^- and \mathbf{b}_2 , γ_2 is the angle between the vectors ξ^- and \mathbf{b}_3 , $|\mathbf{e}_i| = 0(1)\delta$, $i = 1, 2, 3$. Notice that $\gamma_2 = \gamma_1 \pm \alpha$. With the above choice of parameters, we have when δ is sufficiently small,

$$\begin{aligned}2 - \left| \frac{(a_1, b_1)}{|(a_1, b_1)|} \cdot \frac{(a_2, b_2)}{|(a_2, b_2)|} \right| - \left| \frac{(a_1, b_1)}{|(a_1, b_1)|} \cdot \frac{(a_3, b_3)}{|(a_3, b_3)|} \right| \\ = 2 - \cos(|\xi^-| \|\mathbf{b}_2\| \cos \gamma_1) - \cos(|\xi^-| \|\mathbf{b}_3\| \cos(\gamma_1 \pm \alpha)) + 0(1)\delta \\ \geq c_0 \eta_0,\end{aligned}$$

where $c_0 > 0$ is a constant independent of δ . Hence, if $\psi_0(\xi) = \int e^{-iv \cdot \xi} dF_0(v)$ and ξ^- varies on \mathcal{C} defined by (2.1), then we have

$$\begin{aligned}(2.2) \quad \psi_0(0) - |\psi_0(\xi^-)| &= 1 - \left| \int_{A^c \cup_{j=1}^3 A_j} e^{-iv \cdot \xi^-} dF_0(v) \right| \\ &\geq \sum_{j=1}^3 \int_{A_j} dF_0(v) - \left| \sum_{j=1}^3 \int_{A_j} e^{-iv \cdot \xi^-} dF_0(v) \right| \\ &= \sum_{j=1}^3 m_j - \left| \sum_{j=1}^3 m_j (a_j + ib_j) \right| \\ &\geq \min\{m_1, m_2, m_3\} \left(3 - \left| \sum_{j=1}^3 (a_j + ib_j) \right| \right) \\ &\geq \frac{1}{3} \min\{m_1, m_2, m_3\} \left\{ 2 - \left| \frac{(a_1, b_1)}{|(a_1, b_1)|} \cdot \frac{(a_2, b_2)}{|(a_2, b_2)|} \right| - \left| \frac{(a_1, b_1)}{|(a_1, b_1)|} \cdot \frac{(a_3, b_3)}{|(a_3, b_3)|} \right| \right\} \\ &\geq \frac{1}{3} \min\{m_1, m_2, m_3\} c_0 \eta_0 := \kappa_0,\end{aligned}$$

because $|a_j + ib_j| \leq 1$ and

$$\begin{aligned}\left| \sum_{j=1}^3 (a_j + ib_j) \right|^2 &\leq \left(|a_1 + ib_1| + \sum_{j=2}^3 |a_j + ib_j| \left| \frac{(a_1, b_1)}{|(a_1, b_1)|} \cdot \frac{(a_j, b_j)}{|(a_j, b_j)|} \right| \right)^2 \\ &\quad + \left(\sum_{j=2}^3 |a_j + ib_j| \left| \frac{(a_1, b_1)}{|(a_1, b_1)|} \times \frac{(a_j, b_j)}{|(a_j, b_j)|} \right| \right)^2 \\ &\leq \left(1 + \sum_{j=2}^3 \left| \frac{(a_1, b_1)}{|(a_1, b_1)|} \cdot \frac{(a_j, b_j)}{|(a_j, b_j)|} \right| \right)^2 + \left(\sum_{j=2}^3 \left| \frac{(a_1, b_1)}{|(a_1, b_1)|} \times \frac{(a_j, b_j)}{|(a_j, b_j)|} \right| \right)^2 \\ &\leq 5 + 2 \sum_{j=2}^3 \left| \frac{(a_1, b_1)}{|(a_1, b_1)|} \cdot \frac{(a_j, b_j)}{|(a_j, b_j)|} \right|.\end{aligned}$$

Since $\psi(t, \xi)$ is continuous (see Theorem 3.1 in the Appendix) and $\psi(0, \xi) = \psi_0(\xi)$, by means of (2.2), there exist $\mu > 0$, $\varepsilon > 0$ and $T > 0$ such that for any ξ^-

belonging to the set

$$(2.3) \quad \mathcal{C}_{\mu,\varepsilon} = \{\eta \in \mathbb{R}^3; d - \mu \leq |\eta| \leq d + \mu, \left| \frac{\eta}{|\eta|} \cdot \left(\frac{\mathbf{b}_2 \times \mathbf{b}_3}{|\mathbf{b}_2 \times \mathbf{b}_3|} \right) \right| \leq \varepsilon\},$$

we have

$$(2.4) \quad 1 - |\psi(t, \xi^-)| \geq \kappa_0/2 \quad \text{for } t \in [0, T].$$

Take a $R > 0$ such that $(d + \mu)/R = \varepsilon/10$. Let $|\xi| \geq R$, and for $\omega = \xi/|\xi| \in \mathbb{S}^2$ take the coordinate $\sigma = (\theta, \phi) \in [0, \pi/2] \times [0, 2\pi]$ with the pole ω . Write

$$\xi^- = \frac{\xi}{2} - \frac{|\xi|}{2}\sigma = \xi^-(\theta, \phi).$$

If θ satisfies

$$d - \mu \leq |\xi^-(\theta, \phi)| = |\xi| \sin \frac{\theta}{2} \leq d + \mu,$$

then there exists an interval $I_\omega \subset [0, 2\pi]$ such that $\xi^-(\theta, \phi) \in \mathcal{C}_{\mu,\varepsilon}$ for $\phi \in I_\omega$ because $\theta/2 \leq \sin^{-1}(d + \mu)/R < \varepsilon/5$ and the set

$$\{\lambda \xi^-(\theta, \phi) \in \mathbb{R}^3; \phi \in [0, 2\pi], 0 \leq \lambda \leq 1\}$$

intersects the plane spanned by \mathbf{b}_2 and \mathbf{b}_3 when $|\omega \cdot (\mathbf{b}_2 \times \mathbf{b}_3)|/|\mathbf{b}_2 \times \mathbf{b}_3| < \cos \theta/2$ (see Figure 2).

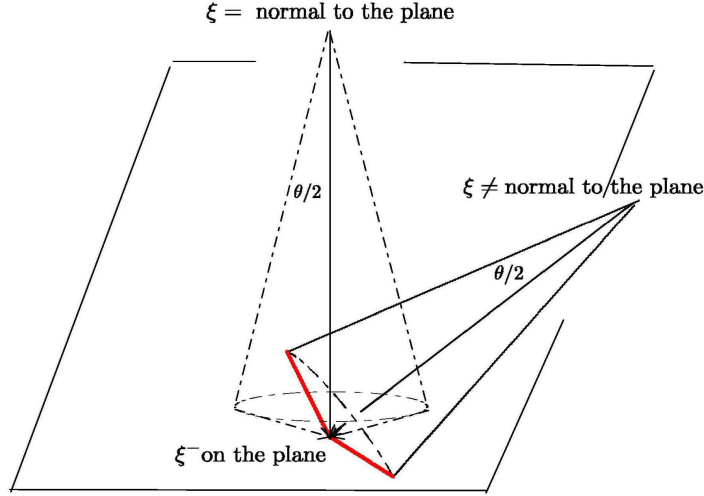


FIGURE 2. Intersection between $\{\xi^-\}$ and the plane spanned by $\mathbf{b}_2, \mathbf{b}_3$

It is obvious that the interval I_ω plays the same role for $\tilde{\omega} \in \mathbb{S}^2$ close to ω . Therefore, for any ξ belonging to a conic neighborhood of ω

$$\Gamma_\omega = \{\xi \in \mathbb{R}^3; \left| \frac{\xi}{|\xi|} - \omega \right| < \varepsilon_\omega, |\xi| \geq R\}$$

with a sufficiently small $\varepsilon_\omega > 0$, we have

$$\begin{aligned}
& \int_{\mathbb{R}^3} \left(\int_{\mathbb{S}^2} b\left(\frac{\xi}{|\xi|} \cdot \sigma\right) \left(1 - |\psi(t, \xi^-)|\right) d\sigma \right) |h(\xi)|^2 d\xi \\
& \gtrsim \int_{\Gamma_\omega} \left(\int_{I_\omega} d\phi \int_{2\sin^{-1}(d-\mu)/|\xi|}^{2\sin^{-1}(d+\mu)/|\xi|} \theta^{-1-2s} \frac{\kappa_0}{2} d\theta \right) |h(\xi)|^2 d\xi \\
& \gtrsim \int_{\Gamma_\omega} |\xi|^{2s} |h(\xi)|^2 d\xi,
\end{aligned}$$

which together with the standard covering argument on \mathbb{S}^2 yields

$$\begin{aligned}
& \int_{\mathbb{R}^3} \left(\int_{\mathbb{S}^2} b\left(\frac{\xi}{|\xi|} \cdot \sigma\right) \left(1 - |\psi(t, \xi^-)|\right) d\sigma \right) |h(\xi)|^2 d\xi \\
& + \int_{\mathbb{R}^3} |h(\xi)|^2 d\xi \gtrsim \int_{\mathbb{R}^3} \langle \xi \rangle^{2s} |h(\xi)|^2 d\xi,
\end{aligned}$$

if $t \in [0, T]$.

2.2. Initial measure concentrated on a straight line. We now consider the case when $F_0(v)$ is concentrated on a straight line and not equal to a single Dirac measure. By means of a suitable choice of the coordinate we may assume that $F_0(v) = \delta(v') F_{03}(v_3)$ and its Fourier transform $\psi_0(\xi) = \psi_{03}(\xi_3)$, where ψ_{03} is the Fourier transform of F_{03} . Since $F_{03}(v_3)$ is not a point Dirac measure in \mathbb{R} , it follows from Corollary 3.5.11 in [11] that there exists a $\xi_{03} > 0$ such that $|\psi_{03}(\pm \xi_{03})| < 1$, in view of $\psi(-\xi) = \overline{\psi(\xi)}$. By means of the continuity of ψ , there exist $0 < \kappa < 1$ and $0 < a_1 < a_2$ such that

$$(2.5) \quad |\psi_0(\xi', \xi_3)| \leq 1 - \kappa, \quad \text{for } \forall \xi' \in \mathbb{R}^2, \forall \xi_3 \in \mathbb{R} \text{ with } a_1 \leq |\xi_3| \leq a_2.$$

We now split the discussion into two cases.

2.2.1. The case when ξ^- is almost orthogonal to the third axis. For the sake of simplicity, we denote ξ^- by ξ throughout this subsection except for the case when confusion might occur. We also denote ψ instead of ψ_0 for brevity.

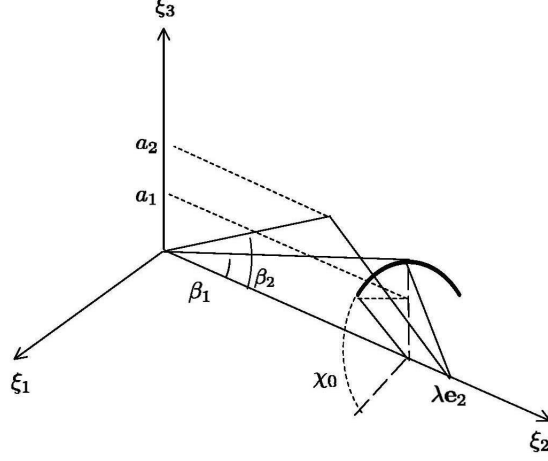
Note that

$$\begin{aligned}
(\partial_t |\psi|^2)(0, \xi) &= 2 \operatorname{Re} \int_{\mathbb{S}^2} b\left(\frac{\xi}{|\xi|} \cdot \sigma\right) \left(\psi^+ \psi^- \overline{\psi} - |\psi|^2\right) d\sigma \\
&= - \int_{\mathbb{S}^2} b\left(\frac{\xi}{|\xi|} \cdot \sigma\right) \left(|\psi^+|^2 + |\psi|^2 - 2 \operatorname{Re}\{\psi^- \psi^+ \overline{\psi}\}\right) d\sigma \\
&\quad + \int_{\mathbb{S}^2} b\left(\frac{\xi}{|\xi|} \cdot \sigma\right) \left(|\psi^+|^2 - |\psi|^2\right) d\sigma \\
&\leq - \int_{\mathbb{S}^2} b\left(\frac{\xi}{|\xi|} \cdot \sigma\right) \left(1 - \psi^-\right) \left(|\psi^+|^2 + |\psi|^2\right) d\sigma \\
&\quad + \int_{\mathbb{S}^2} b\left(\frac{\xi}{|\xi|} \cdot \sigma\right) \left(|\psi^+|^2 - |\psi|^2\right) d\sigma.
\end{aligned}$$

If we put $\xi = \lambda \mathbf{e}_2$ ($\lambda > 0$) in the above estimate and take the polar coordinate $\sigma = (2\beta, \chi) \in [0, \pi/2] \times [0, 2\pi]$, (where χ starting from $\xi_3 = 0$, see Figure 3) then

$$(\partial_t |\psi|^2)(0, \lambda \mathbf{e}_2) \leq -2 \int_0^{\pi/4} d\beta \int_0^{2\pi} d\chi b(\cos 2\beta)(\sin 2\beta) \left(1 - |\psi_3(\lambda \cos \beta \sin \chi)|\right),$$

because $\psi(\lambda \mathbf{e}_2) = 1$ and $|\psi| \leq 1$. Choose $0 < \beta_1 < \beta_2 < \pi/4$, $\chi_0 \in (0, \pi/2)$ and

FIGURE 3. ξ^- with $\beta = \beta_1$ and $\chi \in [\chi_0, \pi - \chi_0]$

$\lambda > 0$ such that

$$\begin{aligned} \lambda \cos \beta_2 \sin \chi_0 &= a_1, \quad \lambda \cos \beta_1 = a_2, \\ 2 \int_{\beta_1}^{\beta_2} b(\cos 2\beta)(\sin 2\beta) d\beta &= c_0 > 0. \end{aligned}$$

Then it follows from (2.5) that

$$(\partial_t |\psi|^2)(0, \lambda \mathbf{e}_2) \leq -2 \int_{\beta_1}^{\beta_2} d\beta \int_{\chi_0}^{\pi - \chi_0} d\chi b(\cos 2\beta)(\sin 2\beta) \kappa = -\kappa c_0 (\pi - 2\chi_0).$$

Since ψ is symmetric around ξ_3 axis, we have

$$(\partial_t |\psi|^2)(0, \xi) \leq -\kappa c_0 (\pi - 2\chi_0), \quad \text{if } \xi \cdot \mathbf{e}_3 = 0 \text{ and } |\xi| = \lambda.$$

If we set $c_1 = \kappa c_0 (\pi - 2\chi_0)$, then there exist $\varepsilon > 0$, $T > 0$ and $\delta > 0$ such that

$$\begin{aligned} (\partial_t |\psi|^2)(t, \xi) &\leq -c_1/2, \\ \text{when } (t, \xi) &\in [0, T] \times \left\{ \xi \in \mathbb{R}^3; \left| |\xi| - \lambda \right| \leq \delta, \left| \frac{\xi}{|\xi|} \cdot \mathbf{e}_3 \right| \leq 2\varepsilon \right\} := [0, T] \times \Gamma, \end{aligned}$$

because of the continuity of ψ and $\partial_t \psi$ (see Theorem 3.1 in the Appendix).

In what follows we use the notation $\xi^- = (\xi - |\xi|\sigma)/2$ to obtain the microlocal time degenerate coercivity estimate. If (t, ξ^-) belongs to the region $[0, T] \times \Gamma$, then it follows from the mean value theorem that there exists a $\rho \in (0, 1)$ such that

$$\begin{aligned} 1 - |\psi(t, \xi^-)| &\geq \frac{1 - |\psi(t, \xi^-)|^2}{2} = \frac{1}{2} \left(1 - |\psi(0, \xi^-)|^2 - (\partial_t |\psi|^2)(\rho t, \xi^-) t \right) \\ &\geq \frac{c_1}{4} t. \end{aligned}$$

Set $R_0 = (\lambda + \delta)/\varepsilon$ and

$$(2.6) \quad \Omega_0 = \{ \xi \in \mathbb{R}^3; |\xi| \geq R_0, \left| 1 - \left| \frac{\xi}{|\xi|} \cdot \mathbf{e}_3 \right| \right| \leq \frac{2\varepsilon^2}{\pi^2} \} \quad (\text{see Figure 4}).$$

If $\sigma = (\theta, \phi)$, we notice that $|\xi^-| = |\xi| \sin(\theta/2)$. Moreover, the fact that $\xi \in \Omega_0$ and $\sin \frac{\theta}{2} \leq (\lambda + \delta)/|\xi|$ implies $\left| \frac{\xi^-}{|\xi^-|} \cdot \mathbf{e}_3 \right| \leq 2\varepsilon$. Therefore, if $t \in [0, T]$ and if

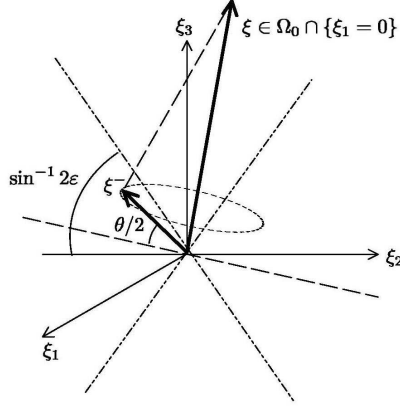


FIGURE 4. $\xi \in \Omega_0$ and ξ^- almost orthogonal to ξ_3

$h(\xi) \in L_s^2(\mathbb{R}^3)$, then we have the micolocal coercivity estimate in Ω_0

$$\begin{aligned} & \int_{\mathbb{R}^3} \left(\int_{\mathbb{S}^2} b\left(\frac{\xi}{|\xi|} \cdot \sigma\right) (1 - |\psi(t, \xi^-)|) d\sigma \right) |h(\xi)|^2 d\xi \\ & \gtrsim \int_{\Omega_0} \left(\int_{2 \sin^{-1}(\lambda - \delta)/|\xi|}^{2 \sin^{-1}(\lambda + \delta)/|\xi|} \theta^{-1-2s} \frac{c_1 t}{4} d\theta \right) |h(\xi)|^2 d\xi \\ & \gtrsim t \int_{\Omega_0} |\xi|^{2s} |h(\xi)|^2 d\xi. \end{aligned}$$

2.2.2. The micolocal coercivity estimate in Ω_0^c . In this subsection, we consider the case when ξ belongs to

$$\Omega_1 = \left\{ \xi \in \mathbb{R}^3; \left| 1 - \left| \frac{\xi}{|\xi|} \cdot \mathbf{e}_3 \right| \right| \frac{2\varepsilon^2}{\pi^2} \right\} \subset \Omega_0^c.$$

Fix an arbitrary $\omega \in \mathbb{S}^2 \cap \Omega_1 \cap \{\omega \cdot \mathbf{e}_3 \geq 0\}$. Take a $\lambda > 0$ such that $\lambda \sin \gamma = (a_1 + a_2)/2$, where $\gamma > 2\varepsilon/\pi$ is the angle between ω and \mathbf{e}_3 . If we take the polar coordinate $\sigma = (\theta, \phi) \in [0, \pi/2] \times [0, 2\pi]$ with the pole $\omega = \xi/|\xi|$ and ϕ starting from the plane $\xi_1 = 0$ (see Figure 5), then we have

$$(2.7) \quad \xi^- \cdot \mathbf{e}_3 = |\xi^-| \left(\cos \frac{\theta}{2} \cos \phi \sin \gamma + \sin \frac{\theta}{2} \cos \gamma \right),$$

where $\xi^- = (\xi - |\xi|\sigma)/2$. There exist $\delta = \delta_\omega > 0$, $\phi_\omega \in (0, \pi/4]$ and $\theta_\omega \in [0, \pi/4]$ such that

$$(2.8) \quad \begin{aligned} a_1 & < (\lambda - \delta) \cos(\theta_\omega/2) \cos \phi_\omega \sin \gamma \\ & < (\lambda + \delta) \left(\sin \gamma + \tan \theta_\omega/2 \right) < a_2. \end{aligned}$$

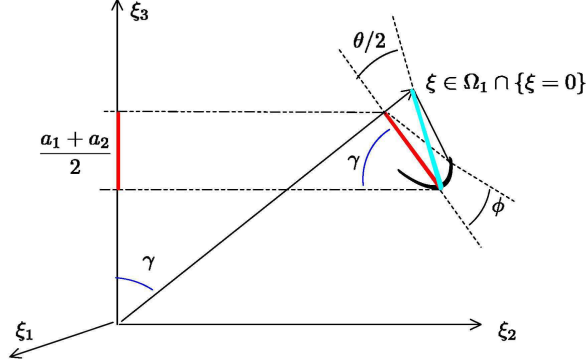


FIGURE 5. Case: $|\xi^- \cdot \mathbf{e}_3| \cos(\theta/2) = (a_1 + a_2)/2$ and $\xi^- \in \{\xi_1 = 0\}$

Put $R_\omega \sin \theta_\omega/2 = \lambda + \delta_\omega$ and let $\xi = |\xi|\omega$ with $|\xi| \geq R_\omega$. If $|\xi^-| = |\xi| \sin \theta/2 \in [\lambda - \delta, \lambda + \delta]$ and $|\xi| \geq R_\omega$, then $\theta \leq \theta_\omega$. Moreover, when $|\phi| \leq \phi_\omega$ we have

$$(2.9) \quad \xi^- \cdot \mathbf{e}_3 \in (a_1, a_2).$$

Since (2.8) still holds for other $\tilde{\gamma}$ close to γ , we have (2.9) for any ξ belonging to a conic neighborhood of ω

$$\Gamma_\omega = \{\xi \in \mathbb{R}^3; \left| \frac{\xi}{|\xi|} - \omega \right| < \varepsilon_\omega, |\xi| \geq R_\omega\},$$

with a sufficiently small $\varepsilon_\omega > 0$, if (θ, ϕ) varies in the same region as above. Since $\psi(t, \xi)$ is continuous, it follows from (2.5) that there exists a $T_\omega > 0$ such that for any $t \in [0, T_\omega]$ we have

$$|\psi(t, \xi^-)| \leq 1 - \frac{\kappa}{2} \text{ if } |\xi^-| \in [\lambda - \delta, \lambda + \delta] \text{ and } \xi^- \cdot \mathbf{e}_3 \in [a_1, a_2].$$

Therefore

$$\begin{aligned} & \int_{\mathbb{R}^3} \left(\int_{\mathbb{S}^2} b\left(\frac{\xi}{|\xi|} \cdot \sigma\right) (1 - |\psi(t, \xi^-)|) d\sigma \right) |h(\xi)|^2 d\xi \\ & \gtrsim \int_{\Gamma_\omega} \left(\int_{-\phi_\omega}^{\phi_\omega} d\phi \int_{2 \sin^{-1}(\lambda - \delta)/|\xi|}^{2 \sin^{-1}(\lambda + \delta)/|\xi|} \theta^{-1-2s} \frac{\kappa}{2} d\theta \right) |h(\xi)|^2 d\xi \\ & \gtrsim \int_{\Gamma_\omega} |\xi|^{2s} |h(\xi)|^2 d\xi. \end{aligned}$$

The estimation for $\omega \in \mathbb{S}^2 \cap \Omega_1 \cap \{\omega \cdot \mathbf{e}_3 \leq 0\}$ is similar, so that we omit it for brevity.

2.2.3. The conclusion. By means of the covering argument, we have for a sufficiently large $R > 0$ and a sufficiently small $T > 0$,

$$\begin{aligned} & \int_{\mathbb{R}^3} \left(\int_{\mathbb{S}^2} b\left(\frac{\xi}{|\xi|} \cdot \sigma\right) (1 - |\psi(t, \xi^-)|) d\sigma \right) |h(\xi)|^2 d\xi \\ & \gtrsim t \int_{\{|\xi| \geq R\}} |\xi|^{2s} |h(\xi)|^2 d\xi, \quad t \in [0, T]. \end{aligned}$$

This together with the coercivity estimate obtained in the first subsection concludes the proof of Lemma 1.4.

Before ending this subsection, we remark that if $\psi_0(\xi) = \int e^{-iv \cdot \xi} dF_0(v)$, then for a large $R > 0$ we have the following degenerate coercivity estimate

$$(2.10) \quad \begin{aligned} & \int_{\mathbb{R}^3} \left(\int_{\mathbb{S}^2} b\left(\frac{\xi}{|\xi|} \cdot \sigma\right) (1 - |\psi_0(\xi^-)|) d\sigma \right) |h(\xi)|^2 d\xi \\ & \gtrsim \int_{\{|\xi| \geq R\}} (|\xi_1|^2 + |\xi_2|^2 + |\xi_3|)^s |h(\xi)|^2 d\xi. \end{aligned}$$

Indeed, it follows from (2.7) that

$$\xi^- \cdot \mathbf{e}_3 \sim |\xi|(\theta\gamma \cos \phi + \theta^2) \sim |\xi| \left\{ \theta \left(\frac{|\xi_1|^2 + |\xi_2|^2}{|\xi|^2} \right)^{1/2} \cos \phi + \theta^2 \right\}$$

for sufficiently small γ and θ , and we have

$$\int_{\mathbb{S}^2} b\left(\frac{\xi}{|\xi|} \cdot \sigma\right) (1 - |\psi_0(\xi^-)|) d\sigma \gtrsim \kappa \int_{\mathcal{A}} \theta^{-1-2s} d\theta d\phi,$$

where $\mathcal{A} = \{(\theta, \phi); \xi^- \cdot \mathbf{e}_3 \in [a_1, a_2]\}$. However, this degenerate coercivity estimate is not sufficient to show the smoothing effect because the continuity in $\psi(t, \xi)$ does not imply (2.10) with $\psi_0(\xi^-)$ replaced by $\psi(t, \xi^-)$.

3. APPENDIX

In this appendix we recall the result given in [6, 13], and prove the continuity of $\partial_t \psi(t, \xi)$. For this, assume

$$(3.1) \quad \exists \alpha_0 \in (0, 2] \text{ such that } (\sin \theta/2)^{\alpha_0} b(\cos \theta) \sin \theta \in L^1((0, \pi/2]),$$

which is fulfilled for $b(\cos \theta)$ with (1.4) if $2s < \alpha_0$. As stated in the proof of Theorem 1.3 in the introduction, it follows from the Bobylev formula that the Cauchy problem (1.1)-(1.2) is reduced to (1.10), if $\psi_0(\xi) = \int_{\mathbb{R}^3} e^{-iv \cdot \xi} dF_0(v)$ and $\psi(t, v)$ denotes the Fourier transform of the probability measure solution.

Theorem 3.1. *Assume that $b(\cos \theta)$ satisfies (3.1) for some $\alpha_0 \in (0, 2]$. Then for each $\alpha \in [\alpha_0, 2]$ and every $\psi_0 \in \mathcal{K}^\alpha$ there exists a classical solution $\psi \in C([0, \infty), \mathcal{K}^\alpha)$ of the Cauchy problem (1.10). The solution is unique in the space $C([0, \infty), \mathcal{K}^{\alpha_0})$. Furthermore, if $\alpha \in [\alpha_0, 2]$ and if $\psi(t, \xi), \varphi(t, \xi) \in C([0, \infty), \mathcal{K}^\alpha)$ are two solutions to the Cauchy problem (1.10) with initial data $\psi_0, \varphi_0 \in \mathcal{K}^\alpha$, respectively, then for any $t > 0$ we have*

$$(3.2) \quad \|\psi(t) - \varphi(t)\|_\alpha \leq e^{\lambda_\alpha t} \|\psi_0 - \varphi_0\|_\alpha,$$

where

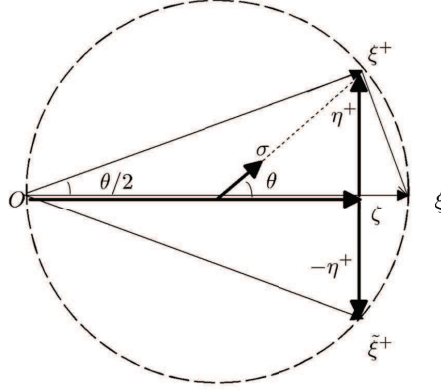
$$(3.3) \quad \lambda_\alpha = 2\pi \int_0^{\pi/2} b(\cos \theta) \left\{ \cos^\alpha \frac{\theta}{2} + \sin^\alpha \frac{\theta}{2} - 1 \right\} \sin \theta d\theta.$$

Furthermore, $\partial_t \psi(t, \xi)$ is continuous in $[0, \infty) \times \mathbb{R}^3$.

The assumption (3.1) with $\alpha = \alpha_0$ can be written as

$$(3.4) \quad (1 - \tau)^{\alpha_0/2} b(\tau) \in L^1([0, 1]),$$

by the change of variable $\tau = \cos \theta$. Theorem 3.1 ameliorates Theorem 2.2 of [6], where (3.4) is assumed with $\alpha_0/2$ replaced by $\alpha_0/4$, see (2.6) of [6]. In what follows,

FIGURE 6. $\cos \theta = \frac{\xi}{|\xi|} \cdot \sigma$, $\eta^+ = \xi^+ - \zeta$

we only prove the last statement of Theorem 3.1 because other parts are already given in [13].

If we put $\zeta = \left(\xi^+ \cdot \frac{\xi}{|\xi|} \right) \frac{\xi}{|\xi|}$ and consider $\tilde{\xi}^+ = \zeta - (\xi^+ - \zeta)$, (which is symmetric to ξ^+ on \mathbb{S}^2 , see Figure 6) as in [13], then the first equation of (1.10) can be written as

$$\begin{aligned} \partial_t \psi(t, \xi) &= \frac{1}{2} \int_{\mathbb{S}^2} b \left(\frac{\xi \cdot \sigma}{|\xi|} \right) \left(\psi(t, \xi^+) + \psi(t, \tilde{\xi}^+) - 2\psi(t, \zeta) \right) d\sigma \\ &\quad + \int_{\mathbb{S}^2} b \left(\frac{\xi \cdot \sigma}{|\xi|} \right) \left(\psi(t, \zeta) - \psi(t, \xi) \right) d\sigma \\ &\quad + \int_{\mathbb{S}^2} b \left(\frac{\xi \cdot \sigma}{|\xi|} \right) \psi(t, \xi^+) \left(\psi(t, \xi^-) - 1 \right) d\sigma \\ &= I_1(t, \xi) + I_2(t, \xi) + I_3(t, \xi). \end{aligned}$$

Putting $\eta^+ = \xi^+ - \zeta$, we have, under the notation $dF_t(v) = f(t, v)dv$,

$$\begin{aligned} |\psi(t, \xi^+) + \psi(t, \tilde{\xi}^+) - 2\psi(t, \zeta)| &= \left| \int_{\mathbb{R}^3} e^{-i\zeta \cdot v} \left(e^{-i\eta^+ \cdot v} + e^{i\eta^+ \cdot v} - 2 \right) dF_t(v) \right| \\ &\leq \int_{\mathbb{R}^3} |e^{-i\zeta \cdot v}| \left(2 - e^{-i\eta^+ \cdot v} - e^{i\eta^+ \cdot v} \right) dF_t(v) \\ &= 2 - \psi(t, \eta^+) - \psi(t, -\eta^+) \\ &\leq 2 \|1 - \psi(t)\|_\alpha |\eta^+|^\alpha \leq 2e^{\lambda_\alpha t} \|1 - \psi_0\|_\alpha \left(|\xi| \sin(\theta/2) \right)^\alpha, \end{aligned}$$

because $|\eta^+| = |\xi^+| \sin(\theta/2)$ and (3.2) with $\varphi_0 = \varphi(t) = 1$. Hence

$$|I_1(t, \xi)| \leq 4\pi e^{\lambda_\alpha t} \|1 - \psi_0\|_\alpha |\xi|^\alpha \int_0^{\pi/2} \sin^\alpha(\theta/2) b(\cos \theta) \sin \theta d\theta,$$

which together with the Lebesgue convergence theorem shows

$$\lim_{(t, \xi) \rightarrow (t_0, \xi_0)} I_1(t, \xi) = I_1(t_0, \xi_0).$$

In order to show similar estimates hold for I_2, I_3 , we recall (19) of Lemma 2.1 in [13], that is, the fact that if $\varphi \in \mathcal{K}^\alpha$ then we have

$$(3.5) \quad |\varphi(\xi) - \varphi(\xi + \eta)| \leq \|\varphi - 1\|_\alpha \left(4|\xi|^{\alpha/2}|\eta|^{\alpha/2} + |\eta|^\alpha \right) \text{ for all } \xi, \eta \in \mathbb{R}^3.$$

Thanks to this with $\eta = \zeta - \xi$,

$$|I_2(t, \xi)| \leq 10\pi e^{\lambda_\alpha t} \|1 - \psi_0\|_\alpha |\xi|^\alpha \int_0^{\pi/2} \sin^\alpha(\theta/2) b(\cos \theta) \sin \theta d\theta,$$

because $|\zeta - \xi| = |\xi| \sin^2(\theta/2)$. Note that similar estimate holds for I_3 . Hence, we obtain the continuity of $\partial_t \psi(t, \xi)$.

Acknowledgements : The research of the first author was supported by Grant-in-Aid for Scientific Research No.22540187, Japan Society of the Promotion of Science. The second author's research was supported by the General Research Fund of Hong Kong, CityU No.103109. The authors would like to thank Professor Villani for the stimulating discussion on this topic.

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